

EMULSION POLYMERS FOR SOIL STABILIZATION

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PRESENTED FOR THE
2004 FAA WORLDWIDE AIRPORT TECHNOLOGY TRANSFER CONFERENCE
Atlantic City, New Jersey, USA

April 2004

INTRODUCTION

Stabilization of soils to improve strength and durability properties often relies on cement, lime, fly ash, and asphalt emulsion. These materials are inexpensive, relatively easy to apply, and provide benefits to many different soil types. However, there are a variety of non-traditional soil stabilization/modification additives available from the commercial sector such as polymer emulsions, acids, lignin derivatives, enzymes, tree resin emulsions, and silicates. These additives may be in liquid or solid form and are often touted to be applicable for most soils. Previous research studies in this area have demonstrated that many soil additives have little to no benefit for silty, sandy soil types [1]. Sandy soils are problematic for stabilization and often require cement and/or asphalt emulsion to provide cohesion for the soil. Generally, lime works well with most clay soils, and cements and asphalt emulsions can be used for a wide range of soils. For clay soils, the clay fraction may often be altered through chemical reaction or ion exchange (such as with lime).

The US Army research effort has been narrowed from evaluating a wide number of soil stabilization/modification additives [1] to a focus on additives with particle binding properties (cements, polymer emulsions, etc.). These materials should be applicable to a wider variety of soil types compared to additives such as acids, enzymes, etc. that require some type of chemical reaction with the native soil particle.

Stabilization of soils using polymer emulsion is a straightforward process in that the liquid is simply diluted to the proper amount. The dilution amount is selected to achieve the target additive quantity at the desired moisture content required for the most efficient compaction of the soil. For field applications, the emulsion is best applied with a spray bar mounted inside the cowling of a reclaimer/stabilizer machine. The application conditions must be well controlled to insure that the proper amount of stabilizer is delivered into the soil and to achieve the proper moisture content for compaction. It should be noted that field mixing is rarely as efficient as laboratory specimen preparation; therefore, the results presented herein are likely to be a “best-case” scenario for stabilization.

The results presented herein are analyzed in terms of unconfined compressive (UC) testing. The use of the UC test was selected to allow for a rapid screening of a variety of different stabilizers and soil types. It is well recognized that other tests such as CBR (California Bearing Ratio) triaxial (confined and unconfined), resilient modulus, and cyclic wet-dry testing are valid tests when considering performance of the stabilized soils. However, the purpose of this work is to demonstrate the differences between emulsion types and to recognize that the emulsions impart significant ductility to the stabilized soils. Hence, the data are analyzed in terms of both unconfined compressive strength (UCS) and toughness.

BACKGROUND

Emulsions represent a huge commercial industry, ranging in applications from food and cosmetics to paints and road construction [2]. Stabilization of soils using asphalt emulsions has been widely applied and is often employed with recycling equipment to perform “cold-mix” recycling to rehabilitate deteriorated pavements. Polymer emulsions are a class of materials in which the polymer is generally manufactured in the emulsion state. They represent a wide-range

of materials from styrene-butadiene random copolymers (synthetic rubber) to polyvinyl chloride (PVC) and many types of acrylic-based polymers employed in paints. Emulsions are a very useful technology in that they often do not require a solvent carrier, are easily cleaned up using water/detergent, and, for many polymers, do not pose an environmental concern when used in bulk.

Polymer emulsions can have a wide range of properties. The emulsions ionic state may be anionic, cationic, or non-ionic. It may be acidic, basic, or neutral pH and the solids content may vary. A typical polymer emulsion contains approximately 40-45% polymer, 1-2% emulsifier with the balance being potable water. The polymer may also be highly variable in its chemistry (i.e. styrene-butadiene or polyethylene-vinyl acetate), molecular weight, degree of branching, side-chain size and composition, etc. Typically, a polymer for soil stabilization should have excellent physical properties such as high tensile, flexural, and compressive strengths, good adhesion to soil particles, and high resistance to water, chemical, and ultraviolet effects. Most of the polymer products touted for soil stabilization are vinyl acetate or acrylic-based copolymers.

Although there is a large body of research directed towards the study of cement, lime, fly ash, and other traditional stabilizers, there is a scarcity of information on nontraditional stabilizers [1, 3-6]. Recently, some studies detailing the effects of nontraditional stabilizers have surfaced [7]. In this study by Rauch, et al, three non-traditional liquid soil stabilizers were added to a variety of clay and clay soils. The results did not indicate significant changes in Atterberg limits, moisture-density relations, swell, or shear strength. However, it was noted that the tests were all conducted under the manufacturer's recommended conditions and that these conditions may not represent the best concentrations or dilution ratios.

Studies by Santoni *et al.* have shown that the polymer emulsions do provide significant strength gain and added strength under wet conditions [1]. Strength gains, as measured by unconfined compressive tests, demonstrate that the polymer-stabilized soil properties improve with curing time. Curing for the polymer emulsions occurs by 'breaking' of the emulsion and subsequent water loss by evaporation. The breaking of the emulsion occurs when the individual emulsion droplets suspended in the water phase coalesce. This occurs as the emulsion particles 'wet' the surface of the soil particle and the polymer is deposited on the surface. The amount of polymer deposited on the surface of the soil particle depends on the concentration of the polymer added and the degree of mixing with the soil.

MATERIALS

A silty sand (SM) material was manufactured for this study. The blended SM consisted of a local Vicksburg loess (silt, ML), concrete sand, and pea gravel (GP, 100% passing a #4 US Sieve size). Soil properties are presented in Table 1. Compacted samples were 'cured' under controlled temperature and humidity conditions, at 23°C and 50% relative humidity. The curing process allowed the samples to air-dry prior to testing.

Six polymer emulsions were obtained from various manufacturers. The materials were initially selected to represent a cross section of available polymer emulsions commonly employed for soil stabilization. The properties as reported in the Materials Safety Data Sheets are listed in Table 2 along with the percent solids. All of the emulsion formulations are proprietary.

Molecular weight and/or other detailed information such as copolymer content, surfactant amount and type, and other additives were not available. The emulsions were diluted to the appropriate concentration to obtain the optimum moisture content of 5% for the silty sand combination. The amount of emulsion used varied depending on the percent solids content of the emulsion. Percent solids were obtained by drying a known weight of emulsion at 105°C to reach a constant weight. Solids contents of the emulsions ranged from 40-50%. All of the soil-polymers reported here were prepared at emulsion percent solids levels of 2.75% weight of solids to weight of soil.

A level of 2.75% was chosen as a convenient basis for comparison and was based on the optimum emulsion additive concentration from previous research efforts [1]. Portland cement was used as the stabilizer control for comparison of properties to the polymers and was used at concentrations of 2.75%, 6%, and 9%.

SPECIMEN PREPARATION

Optimum moisture content for compaction of the SM material was performed using the modified Proctor method (ASTM D1557). The moisture-density compaction curve is presented in Figure 1. The optimum water content for the unmodified SM material was 5 percent. All samples were prepared at this moisture content to provide an equivalent basis for comparison. Under field conditions, moisture-density relations for each soil/stabilizer combination would be determined. For unconfined compression testing, a SHRP (Strategic Highway Research Program) gyratory compaction machine was used to prepare specimens 102-mm-diameter by 152-mm in height. The gyratory compaction method was used due to the ease and consistency of specimen preparation and ease of extraction from the mold. The gyratory compaction method provided a simple, reproducible, and reduced-effort method of preparing specimens for testing. Additionally, previous gyratory compaction experiments demonstrated the ability of this compactor to approximate modified Proctor compaction [8]. The angle of gyration was set at 1.25° (0.022 rad), the same of that used for asphalt compaction. The ram pressure and number of revolutions were varied to generate different compaction energies. A ram pressure of 870 kPa and 90 revolutions was selected to produce the same densities equivalent to ASTM D 1557 moisture-density compaction for the SM material. A comprehensive explanation of the compatibility between gyratory compaction and ASTM D 1557 compaction is beyond the scope of this paper but can be found in reference [9].

Specimen preparation consisted of six steps: soil preparation, additive preparation, soil-additive mixing, molding, compaction, and curing. The soil was prepared by air drying the blended material to a moisture content of 2 - 3 percent, determining the free water requirements to obtain the desired moisture, and mixing the soil-water to obtain the desired moisture content (see Figure 1). Since the material was an SM, a minimum time of only 1 hour was required to achieve equilibrium of the free moisture. Additive preparation varied depending upon the commercial additive used. Many of the additives required dilution of the concentrated product prior to mixing. The weight of the water used for dilution was combined with free water weight to produce the desired specimen moisture content of five percent. Once the soil and additive preparation procedures were complete, the additive was mixed with soil using a high-speed rotary mixing bit attached to an electric drill. The additive was added to the soil in increments and mixed until a uniform product was achieved. A wide-blade putty knife was used periodically

during mixing to scrape and recombine any materials that adhered to the sides and bottom of the mixing container.

Table 1.
Properties of Source Materials and Blended Silty-sand (SM).

Sieve Sizes		Percent Passing by Weight ^a				
Standard Sieve Sizes	Metric Sizes (mm)	Concrete Sand	Loess Silt	Pea Gravel	Silty Sand Blend	Desired Gradation
1	25.4	100.0	100.0	100.0	100.0	100
0.75	19.1	100.0	100.0	99.0	99.6	
0.5	12.7	100.0	100.0	97.3	98.9	
0.375	9.5	99.8	100.0	88.6	95.4	60-100
4	4.8	95.7	99.0	20.7	66.4	50-85
8	2.4	87.6	98.5	11.0	59.1	40-70
16	1.2	79.4	98.0	6.3	53.9	40-70
30	0.5	70.1	97.8	4.8	49.5	25-45
50	0.3	23.7	97.5	1.9	29.7	25-45
100	0.15	2.3	97.3	1.1	20.8	
200	0.08	1.5	97.0	0.7	20.3	12-30
	0.05		94.0		18.8	
	0.01		23.0		4.6	
	0.005		14.0		2.8	
	0.001		11.0		2.2	
D ₁₀		0.204	0.001	2.15	0.025	
D ₃₀		0.33	0.014	5.44	0.30	
D ₆₀		0.50	0.031	7.52	2.70	
C _u or LL		2.43	LL ^b = 30%	3.50	NP ^c	
C _c or PI		1.08	PI ^c = 4%	1.83	NP ^c	
Classification ^b :		SP	ML	GP	SM	

^a Gradations were determined according to ASTM D 442.

^b Liquid Limit (LL), Plasticity Index (PI), and Nonplasticity (NP) were determined according to ASTM D 4318.

^c Soils classified according to ASTM D 2487.

Table 2.
Properties of Polymer Emulsions.

Polymer Emulsion	Chemical Type	% Solids ^a
P1	Acrylic vinyl acetate copolymer	47
P2	Polyethylene-vinyl acetate copolymer	45
P3	Acrylic copolymer	43
P4	Polymeric Proprietary Inorganic Acrylic Copolymer	45
P5	Acrylic vinyl acetate copolymer	42
P6	Acrylic polymer	41

^a percent remaining solids after heating at 105°C to constant weight

during mixing to scrape and recombine any materials that adhered to the sides and bottom of the mixing container.

A sample of the mixed material was taken to determine the initial moisture content of the composite material according to ASTM D 4643. An initial quantity of loose material was measured for each specimen that would produce a 152-mm-high compacted specimen. The quantity of material used to mold each specimen was altered slightly after compacting the previous specimen to improve the accuracy of the compacted specimen height. The material was molded using a 102-mm-diameter by 254-mm-high gyratory compaction mold. The material was placed in five layers, and each layer was hand-rodded 25 times with steel rod to reduce the loose height of the material. This was necessary to ensure that all of the loose material would fit within the gyratory compaction mold. The top of the loose material was leveled using 10 blows of a rubber mallet on a 102-mm-diameter steel plate. A 0.254-mm-thick circular polypropylene membrane was placed on each end of the specimen to prevent adherence to the top and bottom mold plates. Once molded, the specimens were placed in the gyratory device and compacted using the procedures described previously for the moisture-density curve development. The compacted specimens were extruded from the gyratory mold using the hydraulic jack extrusion device mounted on the gyratory machine. The height of the compacted sample was recorded by the gyratory device's software, and the compacted sample was weighed to calculate the as-molded wet and dry densities. All six specimens of each test series were compacted within one hour of mixing to achieve a minimum of 95 percent of ASTM D 1557 maximum density.

The compacted specimens were then placed in a temperature-controlled room where they were allowed to cure at 23°C and 50 percent relative humidity for various cure times. The curing process could be considered an air-dried rather than moist curing process. This method of curing was selected to represent field conditions during military construction operations and was also preferred by the suppliers of the nontraditional stabilizers over a moist-cure process. The curing process primarily consisted of the evaporation of moisture from the specimens over time and the hardening or cementation of the additive-soil matrix.



Figure 1. Moisture-Density Curve for Unmodified Silty Sand.

The unconfined compression (UC) tests were conducted using an Instron® 4208 testing system. The Instron® system consists of the test loading instrument and a computer for load-time recording of results. The test specimen was positioned in the test instrument, and a seating mass of 0.45 kg was applied. This initial load was required to ensure satisfactory seating of the compression piston, and it was considered as the zero load when determining the load-deformation relationship. The load was applied to each stabilized specimen at a constant rate of 0.042-mm per second. Each specimen was compressed until it reached a preset axial strain of 0.08 or until it collapsed. Note that the height to diameter ratio of the specimens was 1.5 rather than the traditionally recommended value of 2.0 for UC testing. This was due to the limitations of the size of the compaction mold. It should also be noted that this investigation is a comparative study in which all additives were tested under the same conditions. Emphasis is placed upon comparative performance rather than the ultimate UC strength of the material. The UC strength can be adjusted for a height to diameter ratio of 2.0 as described in ASTM C42.

Six specimens of each mixture were prepared in the manner described above. Three of the six specimens were subjected to UC tests once the designated curing period was complete. These specimens were tested according to the “dry” test procedure. The remaining three specimens were tested according to the “wet” test procedure. Since the probability of exposure to moisture during the stabilized materials performance life in a pavement system is extremely high, a “wet” test procedure was developed to evaluate the stabilized material’s moisture susceptibility. Several wet test procedures were evaluated, but were deemed to be either not representative of field conditions, too complicated for large numbers of repetitions, or too harsh to permit effective specimen evaluation. Thus, a simplistic “wet” test procedure was developed in which the cured specimen was placed on its side in 25.4-mm depth water bath for a period of 15 minutes. The specimen was then removed from the water and allowed to drain for five minutes. The specimen was then subjected to UC testing. This “wet” procedure permitted a visual observation of the susceptibility to moisture, as well as, a physical evaluation of structural strength loss. The time for exposure to moisture was selected as 15 minutes, based upon the deterioration rate of the control specimens [1].

Statistical analysis was conducted using a commercially available SPSS software program [9]. The statistical analysis consisted of a one-way analysis-of-variance (ANOVA) with classification of the means into common groups using Tukey’s honest-significant-difference (HSD) procedure. This statistical method allows the means to be grouped according to the differences in the means, which, for this work, is established at the 95% significance level. The groups are labeled as A, B, C, etc. indicating which means are significantly different. Means with more than one letter designation (i.e. AB) indicate that the means overlap with the adjacent group. This provides a convenient process for easily identifying statistically significant differences between data sets.

DISCUSSION

Use of unconfined compressive strengths (UCS) for soil stabilizers provides a convenient basis for testing and is a quick and simple test for comparative analysis. However, when comparing materials that demonstrate brittle failure to those that fail in ductile fashion, as many materials do, UCS does not capture significant differences between these materials. For UCS, strain behavior is ignored and only the force at the point of maximum applied stress is needed to

determine UCS. It is for this reason that we chose to use an energy basis for comparison, specifically, toughness. Toughness is a measure of the energy absorbed by the system per unit volume, in this case, up to the yield point. The yield point is defined here as the point of maximum applied stress. Mathematically, toughness is simply the energy applied to the specimen divided by the volume. For this case, the energy is measured as the area under the stress-strain curve up to the yield point, divided by the volume of the compacted specimen. Specimen strain is equated to crosshead movement. The soil-polymer systems often do not fail in a brittle fashion and deform to higher strains than soil-cement. Thus, the use of toughness as a comparative tool allows some comparison of both stress and strain properties in one term rather than just stress alone as with UCS. The methodology employed in this work only captures the stress-strain behavior up to the yield point.

The ANOVA analysis was conducted to determine significant differences between stabilizer types (independent variable). The ANOVA was conducted at one, seven, and 28 days cure and on the dry and wet test conditions. The dependent variables were unconfined compressive stress, toughness, retained wet strength (stress), and retained wet toughness. For all cases the ANOVA indicated significant differences between stabilizer types. Tukey's HSD was then applied to determine the overlap of means between groups at the 95% significance level.

Strength Properties

Figures 2-7 present the unconfined compressive strengths and toughness values for the stabilized silty sands. The highest UCS values after one day of curing (Figure 2) were obtained from the cement-stabilized soil for both the wet and dry tests. After one day of curing, no differences were demonstrated between the unstabilized control and all of the polymers except for P1 in the dry condition. For the wet condition, the cement and all of the polymers except for P3 display significant differences from the unstabilized control. For toughness, Figure 3 demonstrates that the strain levels up to yield are significantly different for all of the polymers from the unstabilized control. Soil-polymers P2 and P4 exhibit toughness values above all of the cement-stabilized soils as well. All of the cement-stabilized soils exhibit significantly higher toughness values than the unstabilized soil. For the wet testing, the soil-cement materials and P1 exhibit higher toughness than all of the other polymers and the unstabilized material.

After seven days of curing, the trends in UCS are similar to those observed after one day of curing (Figure 4). The soil-cements exhibit the highest strength values as with the one-day cure time, however, P1 has strength similar to soil-cement at 2.75% content. All of the other polymers display strengths significantly lower than the soil-cements although the magnitude of the difference for P2 and P4 is not very high compared to 2.75% soil-cement. For the wet testing, the trends are also similar to that observed after one day of curing. The soil-cement materials all display significantly higher wet strengths than the polymers, except for P1 compared to 2.75% soil-cement. All of the polymers, except for P3, demonstrate wet strengths higher than the unstabilized control. When comparing the toughness values, Figure 5 shows that several of the polymers exhibit toughness values similar to those of the soil-cement. Polymer P2 demonstrates significantly higher toughness than all other stabilized materials after seven days of curing. The wet test values demonstrate that polymer P2 has the highest toughness values, followed by P4 and P5. Soil-polymer P1 exhibits wet toughness values on the same order as the 6% and 9% soil-cement.

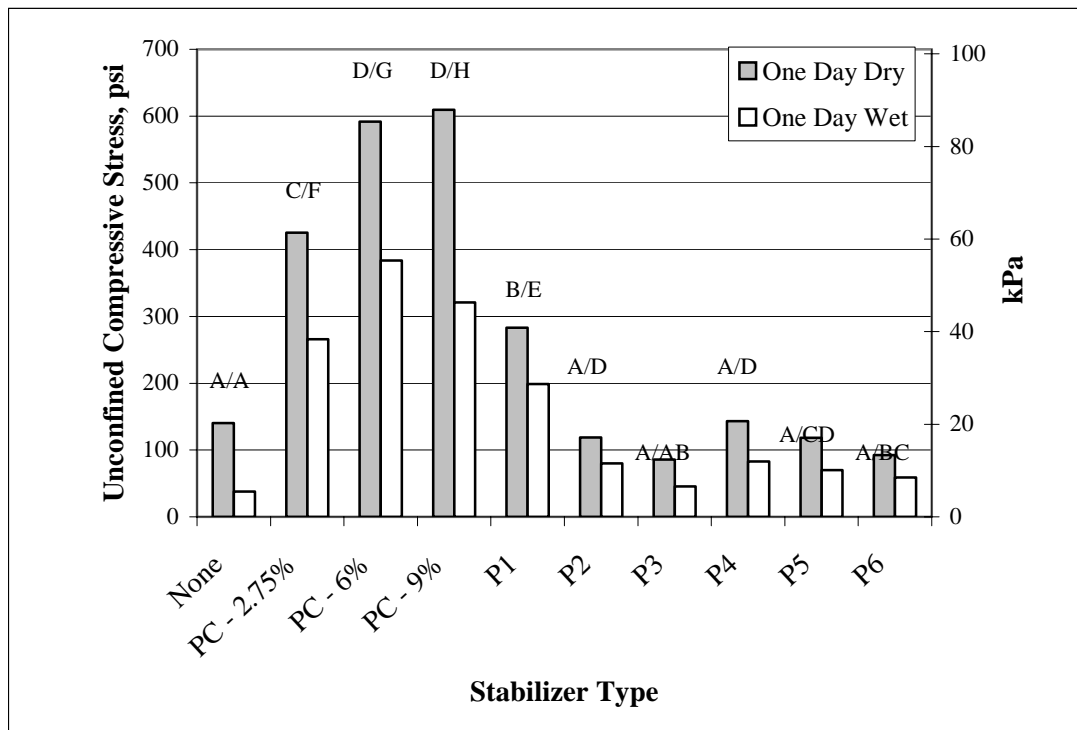


Figure 2. Unconfined compressive strengths values for one day of curing.

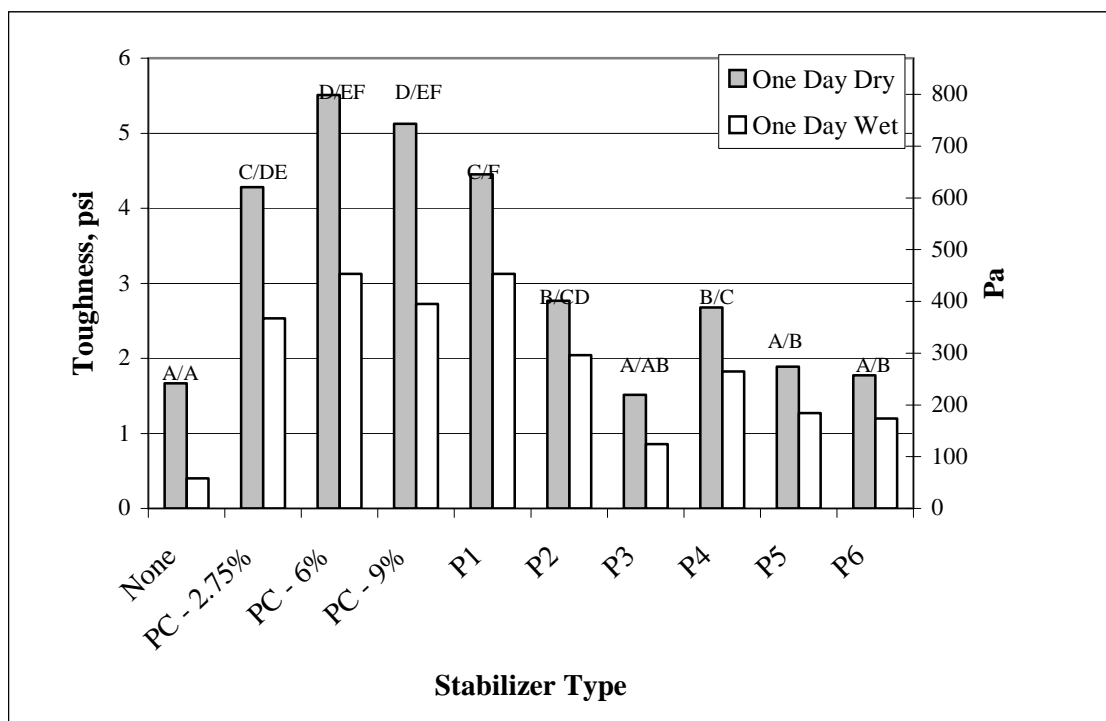


Figure 3. Toughness values for one day of curing.

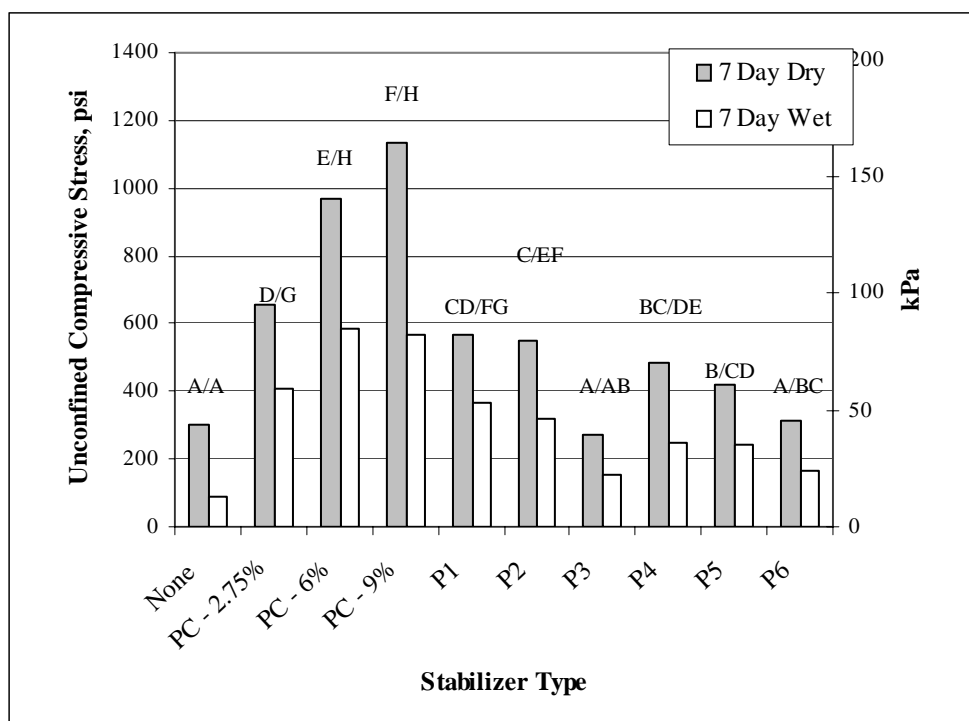


Figure 4. Unconfined compressive strengths values for seven days of curing.

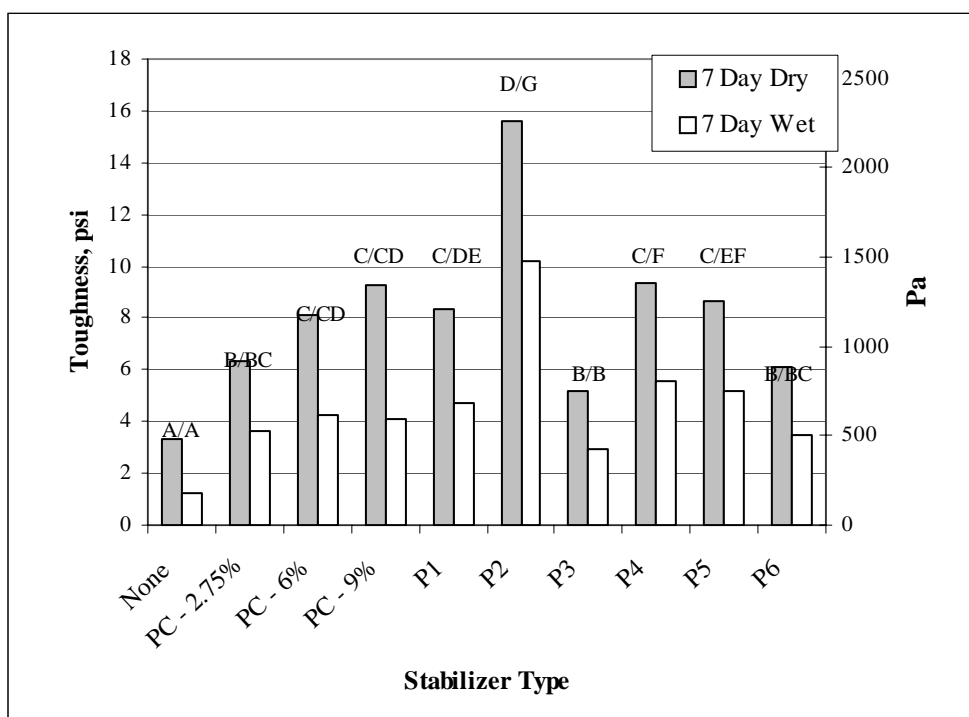


Figure 5. Toughness values for seven days of curing.

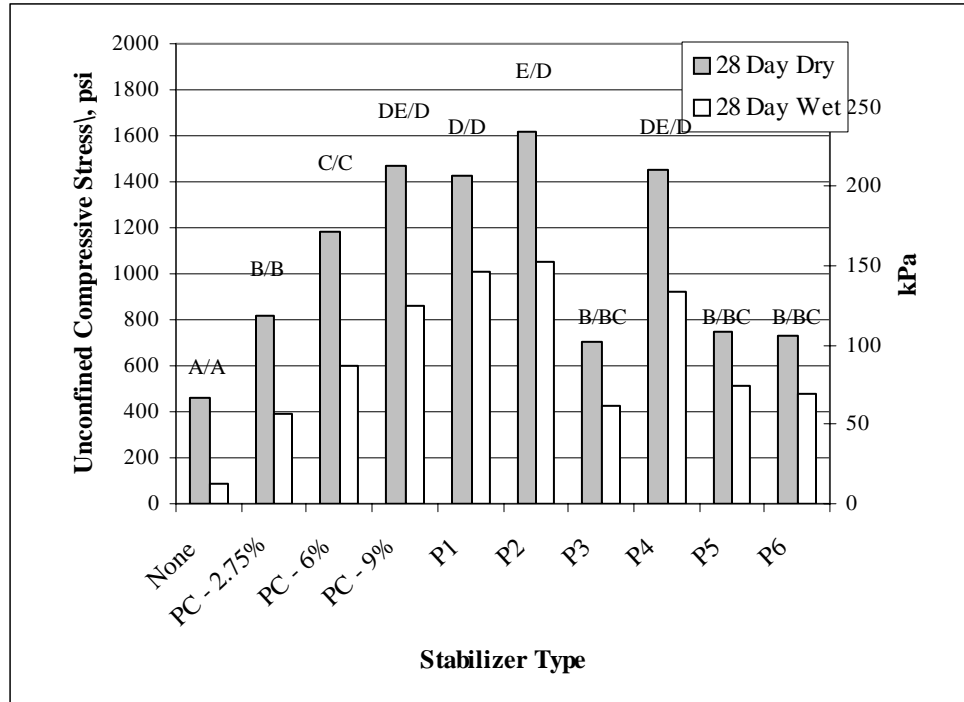


Figure 6. Unconfined compressive strengths values for 28 days of curing.

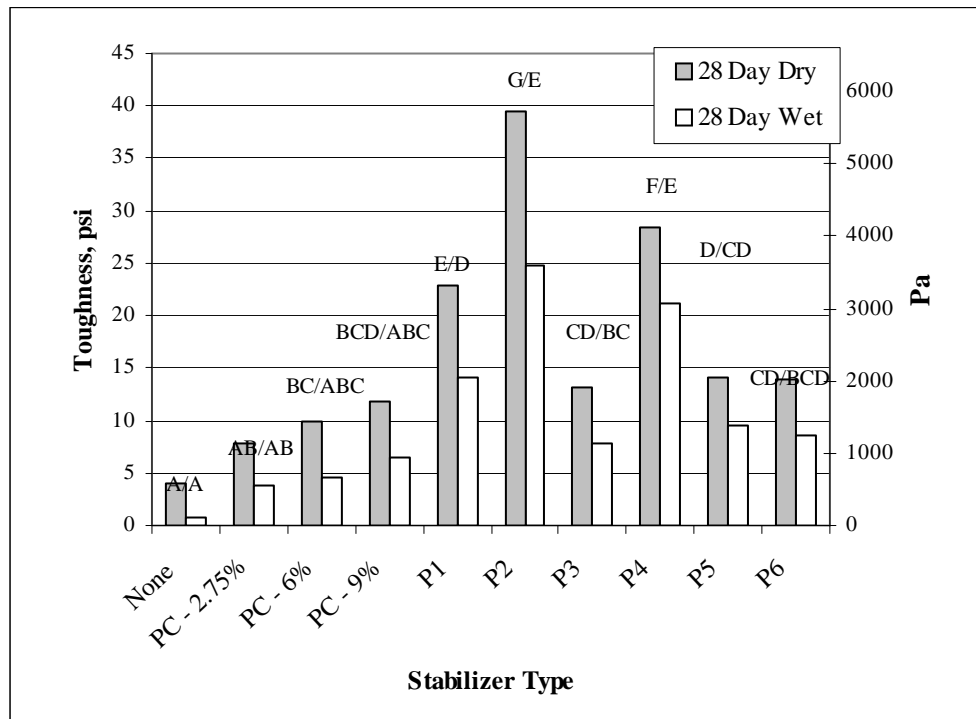


Figure 7. Toughness values for 28 days of curing.

After 28 days of curing, several of the soil-polymers demonstrated UCS values similar to soil-cement and significantly higher than the unstabilized soil (Figure 6). Soil modified with polymers P2 and P4 achieved the highest UC strength along with 9% soil-cement. After the wet test, 9% soil-cement, and soil-polymers P1, P2, and P4 exhibit similar means. Polymer P3, P5, and P6 have wet UCS values on the same order as the 2.75 and 6% soil-cement. When comparing toughness values (Figure 7), polymer P2 demonstrates superior values over any of the other polymer materials tested in this work. Polymers P1, P2, and P4 demonstrate significantly higher toughness values than any of the soil-cements and P3, P5, and P6. After wetting, P1, P2 and P4 exhibit the highest wet toughness values.

Retained Wet Properties

Figures 8 and 9 demonstrate the strength and toughness values, respectively, for the stabilized soils. The wet test is a simple method for providing a quick comparison of strength properties between stabilizers when partially soaked. It is not intended to be a predictor of durability properties related to wet/dry or freeze/thaw but to give a simple indicator of how well a stabilizer responds to the presence of water.

Analysis of variance of the means for the retained strength after the wet test indicated that all of the stabilizers have higher retained wet strength (RWS) than the unstabilized control for all cure times. After one day of cure, polymer P1 exhibited higher RWS than P3 and 9% cement but was not statistically different from the other stabilizers. The retained wet toughness (RWT) of all of the stabilizers was higher than that of the unstabilized control. None of the stabilizers demonstrated significantly different RWT values from one another after one day of cure. As with a one-day cure, after 7 days of curing, all of the stabilizers display higher RWS values than the unstabilized control. However, the RWT values demonstrate that the unstabilized control, 6% and 9% cement have similar RWT values and those polymers P2 and P4 exhibit higher RWT than the other stabilizers. After 28 days of curing, all stabilizers improve the RWS with polymers P1 and P5 being significantly greater than the other polymers. After 28 days of cure, all of the stabilizers improve RWT over the unstabilized control.

Overall, the RWS values for all of the stabilizers were significantly greater than the control. There are a few differences between the polymers and cement, but generally, all of the stabilizers were similar when compared on the basis of UCS. For RWT, the polymers generally exhibit higher values than the cements, indicating the ability to deform to higher strains under similar load conditions.

Effect of Curing Time

The UCS and toughness data are presented as a function of curing time in Figures 10 and 11, respectively. In Figure 10, it is apparent that the strength of the cement mixtures progress logically with 9% cement having higher strength than 6% which, in turn, is higher than 2.75%.

All of the cement-stabilized soils exhibit higher strength when compared to the other stabilizers at both 1 and 7 days. However, polymers P1, P2, and P4 reach significantly higher 28-day strengths than the other soil-polymers P3, P5, and P6. It also appears from the data that P1, P2, and P4 may not have reached their ultimate strengths after 28 days of cure. This is interesting

considering the size of the sample is 102mm diameter (4 inches) and 153-mm (6 inches) in height. In Figure 11, the toughness values clearly show that polymers P1, P2, and P4 are significantly tougher than the other soil additives.

CONCLUSIONS AND RECOMMENDATION

Conclusions

1. All of the soil additives employed in this study increased unconfined compressive strength over the neat soil after 28 days of cure time for both the dry and wet testing conditions. Polymers P1, P2, and P4 at 2.75% weight of solids to weight of soil exhibit unconfined compressive strength values similar to 9% cement after 28 days of cure.
2. Samples prepared with polymer P1 exhibited significantly higher toughness values than all other stabilizers after 28 days of cure. Significantly higher toughness values greater than soil-cement were observed for soil-polymers P1, P2, and P4. As these additives achieved compressive strengths similar to 9% soil cement, the increased toughness values reflect the ability of these soil-polymers to deflect to higher strains prior to yield.
3. All of the additives improved retained wet strength and toughness. The polymer additives had slightly higher wet retained toughness than the cement stabilized soil at 28 days of cure time.
4. The effects of the polymer's native chemical type (see Table 2) were not significant.
5. The UCS and toughness values as a function of curing time demonstrate that several of the polymer additives likely did not reach ultimate properties after 28 days of cure time.

Recommendation

The data reported here indicate that many of the polymer additives significantly improve the physical properties at addition levels below those of typical cement stabilization. Future work will focus on establishing moisture-density relationships, optimizing additive levels, and combinations of emulsions and cement for the better-performing emulsion polymers.

ACKNOWLEDGMENTS

The tests described and the resulting data presented herein, unless otherwise noted, were obtained from research conducted under the Joint Rapid Airfield Construction program of the US Army Corps of Engineers by the Engineer Research and Development Center. Permission was granted by the Chief of Engineers to publish this information.

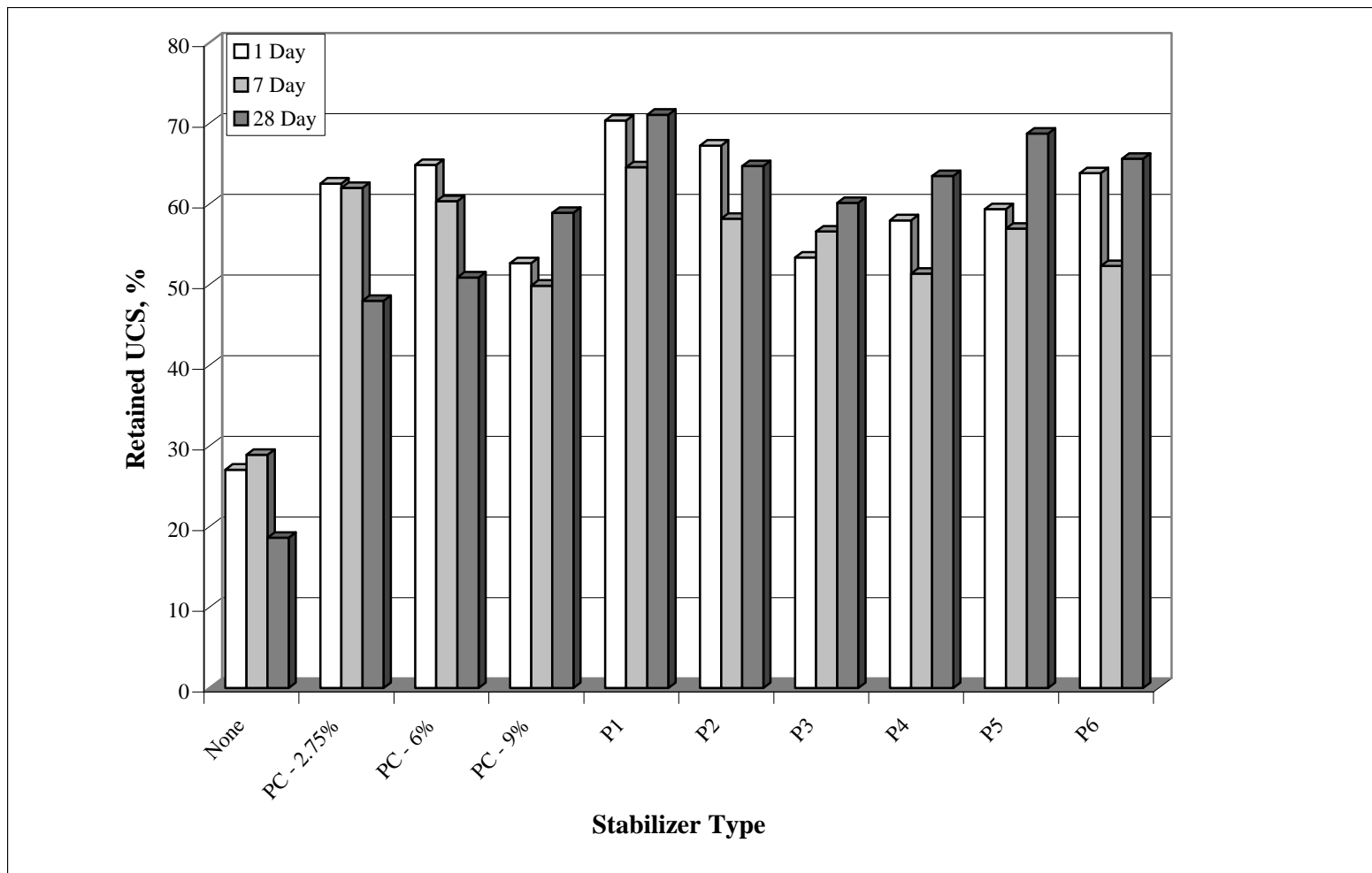


Figure 8. Retained wet unconfined compressive strength values for one, seven, and 28 days of curing.

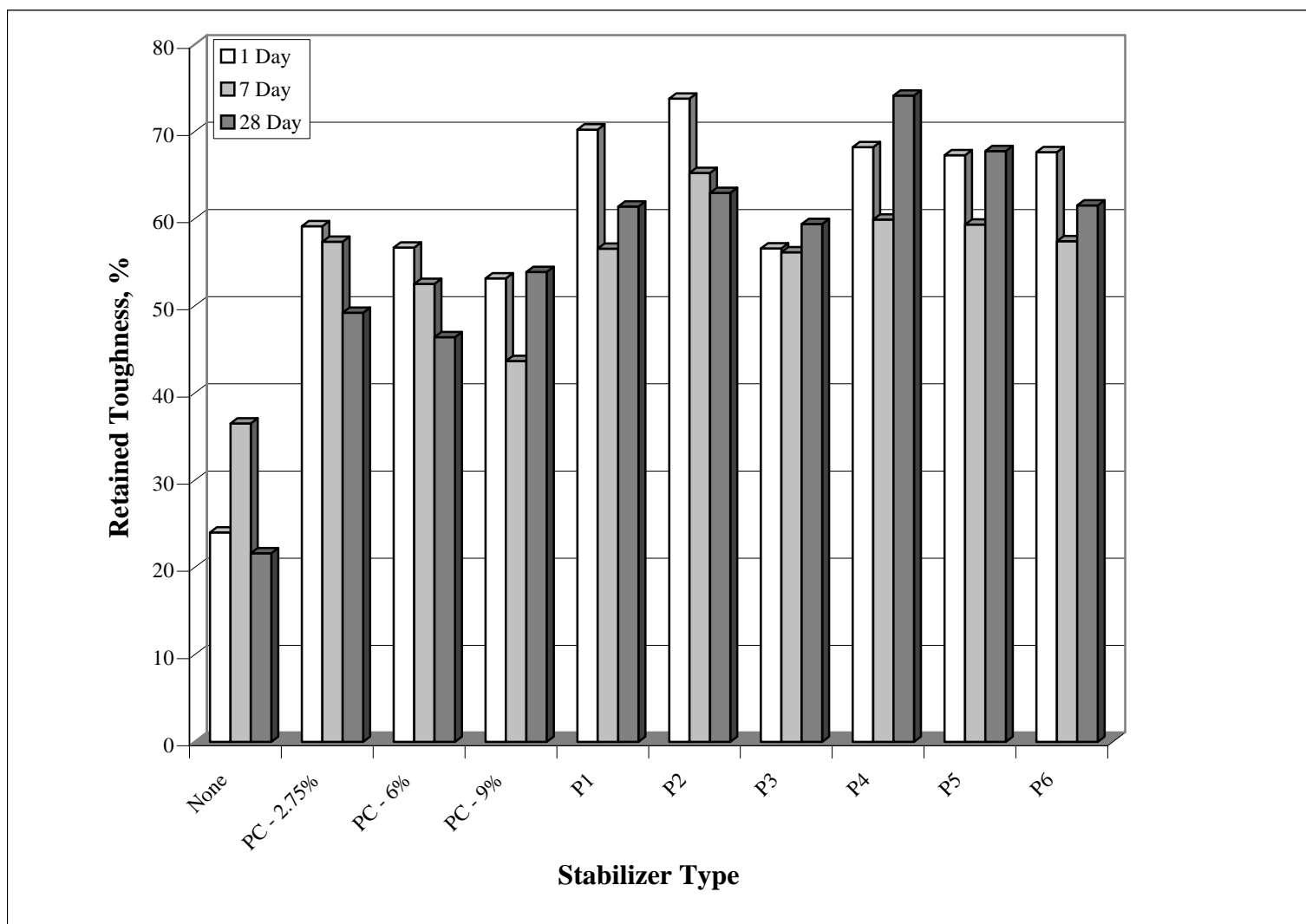


Figure 9. Retained wet toughness values for one, seven, and 28 days of curing.

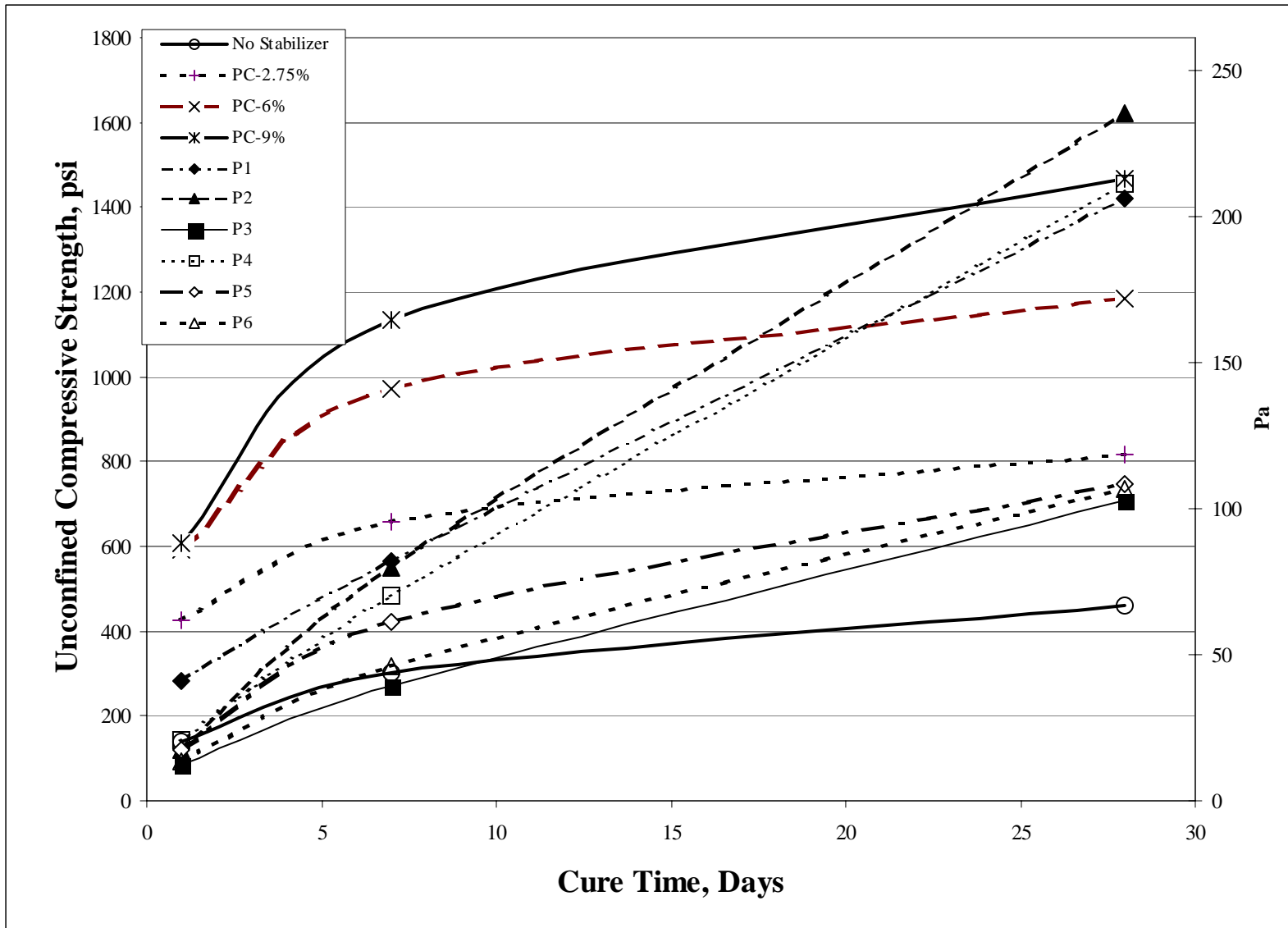


Figure 10. Effect of cure time on unconfined compressive strength.

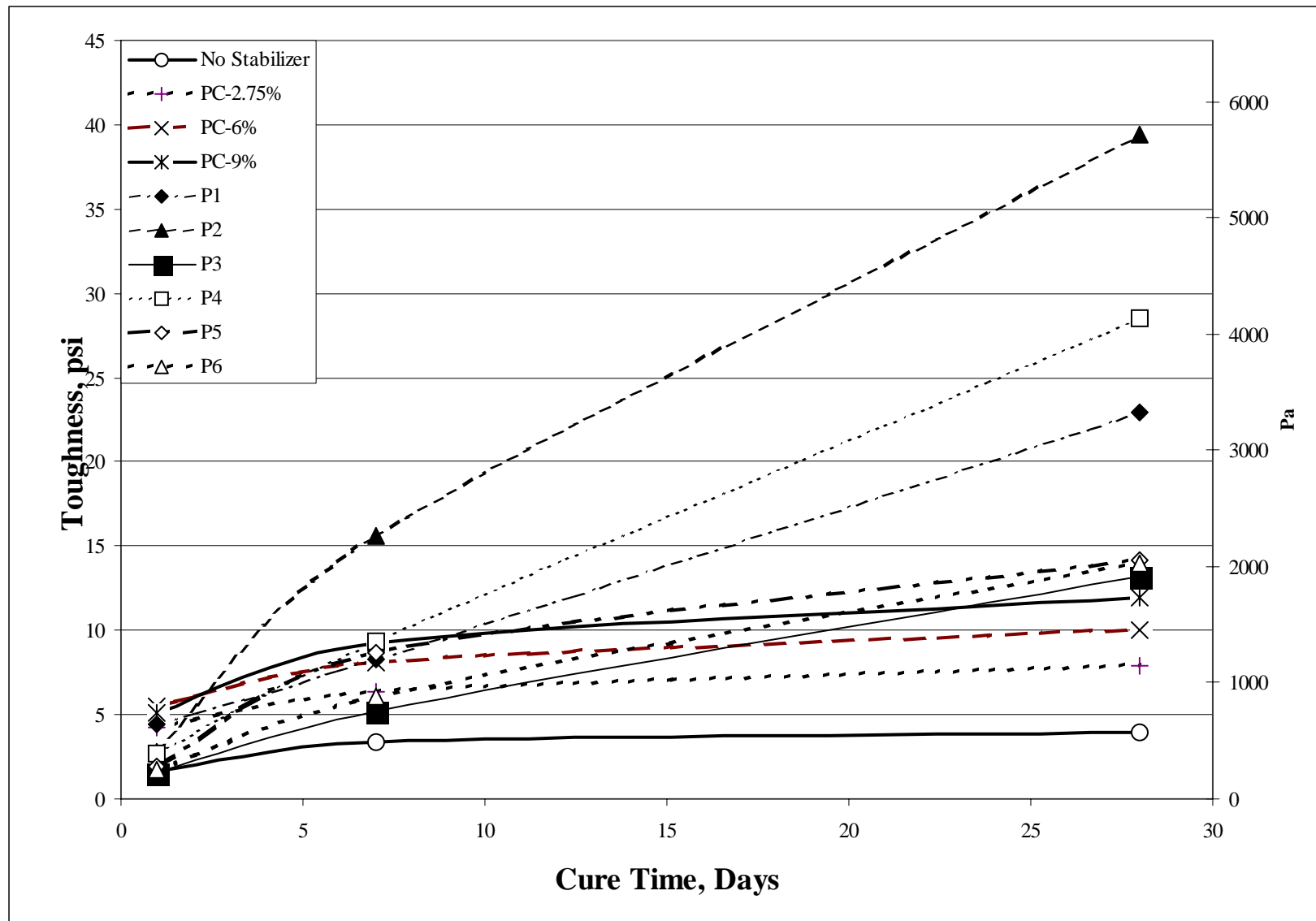


Figure 11. Effect of cure time on unconfined toughness values.

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